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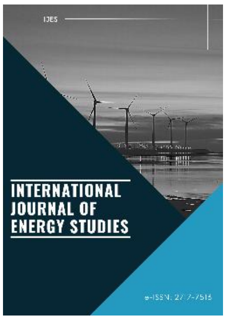

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Comparative assessment of dewatered sewage sludge combustion and biogas production: Environmental, economic and energy considerations

Süleyman Sapmaz[a]

[a] Kocaeli University, Faculty of Technology, Energy Systems Engineering Department, Kocaeli, Turkey, ORCID: 0000-0002-9475-5986

*(*Corresponding Author: suleyman.sapmaz@kocaeli.edu.tr)*

Highlights

- Comprehensive techno-economic model evaluates complete sewage sludge management chain from wastewater plant to final disposal
- High-calorific sludge combustion requires 23.8% less supplementary fuel and achieves emission factor below Turkey's grid (439.88 vs 442 kg CO_2/MWh)
- Biogas production demonstrates consistent low emission performance (780-800 kg CO_2/MWh) but remains economically unfeasible as digestate drying costs exceed all revenues
- Only high-calorific sludge combustion becomes profitable under YEKDEM incentive scheme (133 USD/MWh), generating up to 1.6M USD annually

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ABSTRACT

The escalating production of sewage sludge necessitates sustainable management strategies that balance energy recovery, environmental impact, and economic viability. This study presents a comprehensive techno-economic and environmental comparison of two sewage sludge-to-energy pathways: direct combustion and biogas production through anaerobic digestion. A computational model was developed to evaluate the complete sludge management chain, from wastewater treatment plant discharge to final disposal, accounting for auxiliary fuel requirements in combustion and digestate disposal costs in biogas production. Six sewage sludge (9.57-16.51 MJ/kg) were analyzed using data from Turkish wastewater treatment plants. Results demonstrated that high-calorific sludges required 23.8% less supplementary fuel than low-calorific samples, with installed capacities ranging from 0.84 to 1.58 MW for combustion systems and 0.66 to 0.79 MW for biogas systems. Only the highest calorific sludge achieved an emission factor (439.88 kg CO_2/MWh) lower than Turkey's electricity grid (442 kg CO_2/MWh), while biogas systems exhibited consistent emission factors (780-800 kg CO_2/MWh) across all scenarios. Economic analysis revealed that neither pathway is viable without government incentives at current market prices (67.81 USD/MWh). Total annual emissions from incineration (8,300 tons CO_2/year for low-calorific sludge) substantially exceeded those from biogas production (4,000-4,500 tons CO_2/year).

Keywords: Sewage sludge, Combustion, Anaerobic digestion, Net energy production, Environmental impact

1. INTRODUCTION

The escalating global production of sewage sludge, estimated at approximately 10 million tonnes of dry matter annually within the European Union,necessitates advanced management strategies beyond conventional disposal methods[1]. This surge in sludge generation underscores the urgency for innovative and sustainable solutions that can concurrently mitigate environmental impact and recover valuable resources[2]. Traditional disposal practices, such as landfilling and land application, often present significant environmental challenges due to the presence of heavy metals, pathogens, and organic pollutants within the sludge[3,4]. Consequently, the exploration of waste-to-energy technologies, specifically thermal utilization processes like combustion, gasification, pyrolysis and biological conversion pathways such as anaerobic digestion for biogas production, has gained considerable traction as viable alternatives[5–7]. Despite the extensive academic research devoted to gasification and pyrolysis, these innovative technologies have not been widely implemented in commercial-scale operations[8–11]. Combustion and biogas production represent well-established and widely adopted technologies for sewage sludge disposal, supported by extensive academic research and practical experience. However, a comprehensive techno-economic and environmental comparison of these two prominent approaches remains crucial for informed decision-making in waste management and energy policy.

Dewatered sludge is incinerated in combustion plants or co-incinerated with other fuels, often in fluidized bed combustors, generating heat and electricity while significantly reducing sludge volume[1]. In co-combustion applications, dried sludge is burned as supplementary fuel in existing solid fuel-fired boilers (typically coal, sometimes MSW)[12–14]. However, when autothermal combustion is not achieved, particularly at lower dry solid content, supplementary fuel is often required. This can increase operational costs and greenhouse gas emissions[15].

Carotenuto et al. developed a cogeneration process model based on gasification for energy recovery from sewage sludge. In the model, sludge with an initial moisture content of 48.72% was assumed to be dried until it reached 5.53% total solids (TS) using waste heat from the cogeneration plant. The dried sludge was subsequently processed in a gasifier, and the resulting syngas was utilized in an internal combustion engine (cogeneration unit) to generate both electricity and heat. The examined sludge sample exhibited a lower heating value (LHV) of approximately 13 MJ/kg (3.61 kWh/kg). The energy required for drying was estimated at 0.83 kWh/kg. The study concluded that 1 kg of dry sludge could produce approximately 0.89 kWh of electrical energy and 1.67 kWh of thermal energy under the modeled conditions[16].

Siriwardhana et al. [17], investigated the integration of a fluidized bed dryer with a fluidized bed combustion system. The heat required for drying was supplied by steam generated from the combustion unit. When sludge with a lower heating value (LHV) of 9 MJ/kg was combusted, a total annual energy output of 12,890 GJ was produced, of which approximately, 10,367 GJ/year was consumed by the drying process. Considering additional system losses, the available useful heat was calculated to be around 2,000 GJ/year. Although the fuel cost savings were relatively small (approximately 1,800 USD/year), the replacement of coal resulted in a significant potential reduction in emissions.

Xiao et al. investigated sludge combustion processes, comparing standalone sludge combustion, co-combustion with municipal solid waste or coal, and incineration in cement plants in terms of life cycle environmental impacts and costs. The calorific values of the sludges were relatively low (1.5–2.75 MJ/kg). Sludge was assumed to be dried prior to combustion to increase its dry matter content, with electricity used for drying instead of conventional fuels. The study found that standalone sludge combustion exhibited the highest life cycle costs and the greatest environmental impact among the options considered[12].

Cogeneration systems based on biogas production differ substantially from combustion processes in terms of their operational principles. Biogas production should not be regarded as a final disposal method, as typically 60-90% of the initial organic matter is degraded during anaerobic digestion[18]. Consequently, this process leads to (1) lower overall energy recovery compared to combustion and (2) potential greenhouse gas (GHG) emissions when the digested sludge is subsequently disposed of in landfills[4,17]. It is also important to note that a subsequent drying process is required to enable the final disposal of the digested sludge. This drying step imposes an additional financial and environmental burden, further reducing the overall efficiency and sustainability of the biogas-based system.

The methods used to estimate the amount of biogas that can be produced from sludge (theoretical methane potential) and the resulting CO_2/CH_4 ratio have been extensively studied, with particular focus on the Buswell equation [18–20]. In biogas production from sludge, the system integrations and co-digestion with various biodegradable wastes are being investigated to convert the remaining non-degraded organic fraction into useful energy[21].

Cao et al. conducted a comparative analysis of energy production from wastewater sludge, evaluating the combined application of anaerobic digestion (AD) and pyrolysis against pyrolysis alone. The findings demonstrated that the integrated AD-pyrolysis approach achieved 11-17% higher energy efficiency compared to standalone pyrolysis. For 100 kg of raw sludge, the combined system generated a total of 1,948 MJ of energy, whereas pyrolysis alone produced 1,554 MJ. Biochar produced through pyrolysis exhibits significant potential for carbon sequestration and soil quality enhancement, rather than serving primarily as an energy source[19].

Li et al. investigated the energy potential of solid digestate (SD) from a wet anaerobic digestion process via combustion. The study indicates that drying the SD and including flue-gas condensation (for heat recovery) are necessary to achieve autothermal combustion and recover sufficient heat for the drying process. When a steam turbine cycle is integrated, the electricity generated from burning SD could cover 13-18% of the plant's total electricity consumption, depending on the degree of dryness. Reducing the digestion period from 23 to 18 days significantly increases the SD's heating value and mass flow, which can augment electricity generation by a factor of up to 2.5. However, this reduction in digestion time also decreases biogas production by 13-22%, necessitating a comprehensive economic evaluation to determine the optimal operating conditions[22].

The utilization of sewage sludge for energy production through both combustion and anaerobic digestion (AD) has been extensively investigated in the literature. However, from another perspective, sludge is essentially a waste that must be properly disposed of. Studies focusing on sludge combustion often overlook the net energy production aspect, particularly the need for auxiliary fuel, whereas research on biogas production typically disregards the environmental and financial costs associated with the disposal of digested sludge.

In this study, the entire sludge management process — from the discharge point of the wastewater treatment plant to final disposal — was evaluated comprehensively. Two alternative pathways, direct combustion of dewatered sewage sludge and electricity generation through biogas production, were compared in terms of energy efficiency, cost, and environmental impact. Furthermore, the effect of the feed-in tariff mechanism was analyzed by comparing the incentivized electricity price with the market price. In doing so, the study presents a holistic assessment of the actual financial and environmental costs associated with net energy generation from sewage sludge.

2. MATERIAL AND METHODS

A computational model was developed to evaluate the overall energy balance in both sewage sludge combustion and biogas production processes. The model utilizes analytical data on sludge composition as input parameters and calculates the corresponding energy flows and balances within each process pathway. In the combustion scenario, the model accounts for the thermal energy released from the oxidation of organic matter, as well as the energy required for water evaporation and the heating of flue gases. In the biogas scenario, it estimates the biochemical energy conversion efficiency based on the organic fraction of the sludge and the subsequent energy recovery through biogas combustion for electricity generation. The material and energy flow diagrams associated with the analyzed scenarios are presented in Figure 1.

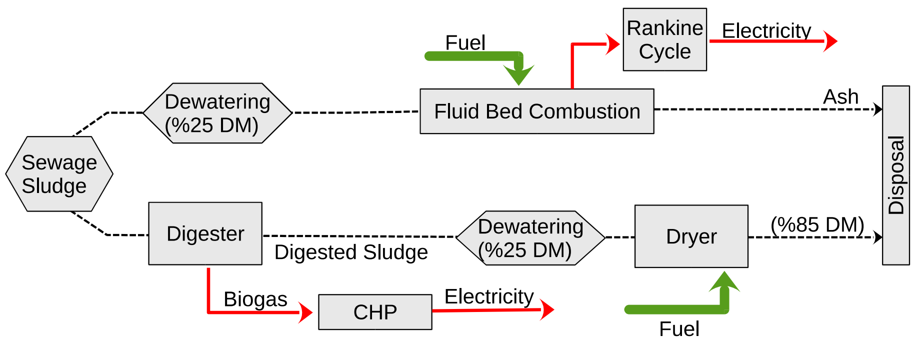

Figure 1. Description of Scenarios

The sewage sludge characteristics used in the study were obtained from the results of the project “Management of Domestic/Urban Wastewater Sludge” which was supported under the “Public Institutions Research and Development Project Support Program” in Türkiye. The project conducted a comprehensive analysis and evaluation of sewage sludge management practices[23,24]. The samples were selected to represent a range of calorific values—high (LHV>15000 kJ/kg), medium (12000 kJ/kg <LHV<15000 kJ/kg), and low (LHV<12000 kJ/kg)—with two samples chosen from each group.

Sludge obtained from dewatering processes typically contains 10-30% solid matter[25]. This value depends on various factors, including the dewatering mechanism applied (e.g. decanter centrifuge, belt press or filter press), as well as the characteristics of the wastewater and the treatment processes. In this study, 25% was adopted as the reference value for solid content, as this figure is widely reported in the literature[26,27].

The moisture content of the sludge after drying is determined by the drying parameters. Modern contact dryers can achieve a drying level of up to 98% dry solids (DS) [28]. For sludge intended for use as fuel, a DS content of 90% is preferred. However, if the dried sludge is stored in an open atmosphere, it may reabsorb moisture, which would make a 90% DS target energetically inefficient. Therefore, this study evaluates drying the sludge to 85% DS content, in line with literature data[29]. The solid content of sludge after the dewatering process and at the dryer outlet determines the drying load. The drying load is directly related to the energy consumption of the drying process and therefore affects the sensitivity of the model. For this reason, it is important that these values are selected in accordance with literature data and realistic operating conditions. The elemental composition of the organic fraction, ash content and calorific values of analyzed SS are given in Table 1.

Table 1. Sewage Sludge Properties

SS	Organic Fraction (%)					ASH (%)	LHV (kJ/kg)
	C	H	O	N	S		
SS-1	43.09	7.43	17.68	1.09	4.96	25.75	16506.72
SS-2	43.14	7.52	16.32	0.74	4.73	27.55	16019.28
SS-3	34.37	5.76	20.13	5.62	0.88	33.24	13408.60
SS-4	34.37	5.76	20.13	0.88	5.62	33.24	13421.44
SS-5	26.9	4.26	17.43	1.23	3.66	46.52	9570.90
SS-6	25.82	3.85	18.66	1.19	2.91	47.57	10278.00

The model consists of two primary computational modules: (1) thermodynamic modeling of sludge combustion and (2) evaluation of anaerobic digestion and biogas potential. The energy balance in the combustion model determines whether sewage sludge can be disposed of without the need for any auxiliary fuel input. In cases where additional fuel is required, the model quantitatively estimates the necessary amount to sustain complete combustion. In the biogas model the energy balance indicates the amount of energy required for drying of SS before disposal (landfill regulations). The thermophysical properties used for heat transfer and energy balance calculations within the model are presented in Table 2.

Table 2. Model Assumptions and Constants

Parameter	Value	Unit
Specific Energy Consumption for Drying (SEC)	3500	kJ/kg
Water specific heat capacity ($C_{p,water}$)	4.18	
Air specific heat capacity ($C_{p,air}$)	1.17	
Steam specific heat capacity ($C_{p,steam}$)	2.102	kJ/kg·K
Ash specific heat capacity ($C_{p,ash}$)	1.045	
Flue gas specific heat capacity ($C_{p,FG}$)	1.5	
Initial Temperature (T_1)	20	
Drying Temperature (T_2)	100	°C
Flue Gas Boiler Exit Temperature (T_3)	850	

2.1. Combustion Model

The combustion model calculates the energy balance associated with the incineration of sewage sludge. In the model, moisture and ash free (MAF) solid fraction of sewage sludge fuel combustion is represented through stoichiometric combustion equations, while the net energy contribution of natural gas is determined using a natural gas combustion submodel. Combustion air is assumed to be dry air.

Fundamental thermodynamic equations are applied to estimate the total energy content of the flue gas components.The products generated from the combustion of dewatered sludge include flue gas (including excess air), water vapor, and ash. It is further assumed that all ash produced during combustion is entrained with the flue gas as fly ash.

The total energy demand for the combustion process was determined using Equation (1). To ensure low combustion emissions, it is a regulatory requirement that the flue gas exits the boiler at a temperature of $850°C$ (T_3). When the energy carried by the combustion products during the temperature rise from T_1 to T_3 equals the energy released from the combustion of sludge solids, autothermal combustion can occur without the need for any additional fuel. However, autothermal combustion is generally not achieved for dewatered sewage sludge. Therefore, in the energy balance (Equation 1), the component defined as Q_{required} represents the amount of additional fuel energy necessary to reach the desired flue gas temperature and ensure complete combustion. The term $Q_{combustionproducts}$ denotes the sensible heat content of the flue gas within the temperature range of T_1– T_3, whereas $Q_{watervapor}$ accounts for the latent and sensible heat associated with the evaporation of water present in the sludge. Q_{ash} corresponds to the sensible heat of the ash fraction, and $Q_{sludge,LHV}$ indicates the chemical energy content of the sludge, expressed as its lower heating value.

$$Q_{\text{required}} = Q_{\text{combustionproducts}} + Q_{\text{watervapor}} + Q_{\text{ash}} - Q_{\text{sludge,LHV}} \quad (1)$$

The specific energy consumption (SEC) required for water evaporation is incorporated into the model based on data reported in the literature for different types of dryers. The specific energy consumption (SEC) values reported for sludge drying typically range between 2500–5000 kJ/kg of water. In contact (conductive) dryers, lower energy consumption levels are achieved, generally within the range of 2220–4320 kJ/kg of water[30]. SEC value is determined as 3500 kJ/kg water. Equation (2) quantifies the energy carried by water vapor. The calculation accounts for the sensible heat of liquid water from 20°C (T_1) to 100°C (T_2), the latent heat of vaporization at 100°C, and the sensible heat of steam from 100°C to 850°C(T_3):

$$Q_{\text{water\_vapor}} = m_{\text{water}}\left[C_{p,\text{water}}(T_2 - T_1) + SEC + C_{p,\text{steam}}(T_3 - T_2)\right] \quad (2)$$

The energy associated with ash is determined using Equation (3), which incorporates the mass of ash m_{ash}, its specific heat capacity $C_{p,\text{ash}}$, and the temperature difference between feed and exhaust conditions:

$$Q_{\text{ash}} = m_{\text{ash}}\, C_{p,\text{ash}}\, (T_3 - T_1) \quad (3)$$

Equation (4) describes the energy carried by the combustion products. The combustion products consist of a mixture of various gases, and the properties of the mixture are calculated by summing the energy contributions of each individual component:

$$Q_{\text{combustion\_products}} = \sum_i n_i \; C_{p,i} \, (T_3 - T_1) \tag{4}$$

2.1.1. Natural Gas Combustion

In the sludge combustion model, the additional energy requirement (Q_{required}) is assumed to be supplied by natural gas. The components resulting from natural gas combustion are expected to exit at the flue gas temperature corresponding to the boiler operating parameters. Accordingly, a portion of the heat released from natural gas combustion is utilized to raise the temperature of the combustion products to 850°C.

The net energy input to the natural gas combustion process is calculated by considering this energy relative to the lower heating value of natural gas. The additional fuel volume required for combustion ($V_{\text{naturalgas}}$), is determined using Equation (5).

$$V_{naturalgas} = \frac{Q_{required}}{Q_{NG,net}} \tag{5}$$

The operational parameters of the combustion plant were determined considering typical industrial practices for sewage sludge incineration and optimal combustion conditions. The established operating parameters are presented in Table 3. The flue gas cleaning processes required after sludge incineration can reduce the overall energy efficiency of the system; however, this effect has been neglected within the scope of this study.

Table 3. Operating Parameters of the Combustion Plant

Parameter	Value	Unit
Sludge excess air ratio (EA_{SS})	30	%
Natural gas excess air ratio (EA_{NG})	15	%
Natural gas density (ρ_{NG})	0.68	kg/m³

2.2. Biogas Model

The biogas model describes the biochemical processes occurring during anaerobic digestion of sewage sludge, including substrate hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These processes govern the growth of microbial biomass and the production of methane in the digester. To model biomass growth and methane production in the anaerobic digestion process, Equations (6–8) are employed [18,19,31]. Here, P_x represents the biomass concentration, and V_{CH_4} denotes the volume of methane produced. Y is the biomass yield, COD represents the chemical oxygen demand of the substrate, k_d is the biomass decay coefficient, and SRT corresponds to the solids retention time.The parameters utilized in the model are listed in Table 2.

$$COD_b \text{ Load } = COD_b\, Q \tag{6}$$

$$P_x = \frac{Y\, COD\, \eta}{1 + k_d\, SRT} \tag{7}$$

$$V_{CH4} = 0.40\, (COD_b \text{Load}\, C) - 1.42\, P_x \tag{8}$$

Table 4. Biogas Model Assumptions[31,32]

Parameter	Value	Unit
Solids retention time (SRT)	18	days
Decay coefficient (k_d)	0.03	day^{-1}
Conversion efficiency (η)	0.70	-
Yield coefficient (Y)	0.08	-

The Buswell equation (Equation 9) allows the stoichiometric estimation of the theoretical chemical oxygen demand ($COD_{\text{theoretical}}$) of an organic compound with a known chemical composition[33]. Using this approach, the COD of the organic fraction of sludge, expressed as $\mathrm{C}_c\mathrm{H}_h\mathrm{O}_o\mathrm{S}_s$, was calculated according to Equation 10.

$$\begin{aligned} \mathrm{C}_c\mathrm{H}_h\mathrm{O}_o\mathrm{N}_n\mathrm{S}_s + \frac{(4c - h - 2o + 3n + 2s)}{4}\mathrm{H_2O} \\ \rightarrow \frac{(4c - h + 2o + 3n + 2s)}{8}\mathrm{CO_2} \\ + \frac{(4c + h - 2o - 3n - 2s)}{8}\mathrm{CH_4} + n\mathrm{NH_3} + s\mathrm{H_2S} \end{aligned} \tag{9}$$

$$COD_{theoretical} = \frac{4c + h - 2o - 3n - 2s}{c + h + o + n + s} \times M_{SS} \times \frac{1}{M_{O_2}} \quad (10)$$

Figure 2 presents the computational framework developed for the comparative analysis of sludge-to-energy pathways. The algorithm begins with input data on sludge composition and properties, followed by separate combustion and biogas modeling modules. Combustion model energy balance calculations determine whether the system operates under autothermal conditions or requires additional fuel input. The final results, including natural gas demand and biogas yield, are exported for integrated energy, environmental, and economic evaluation.

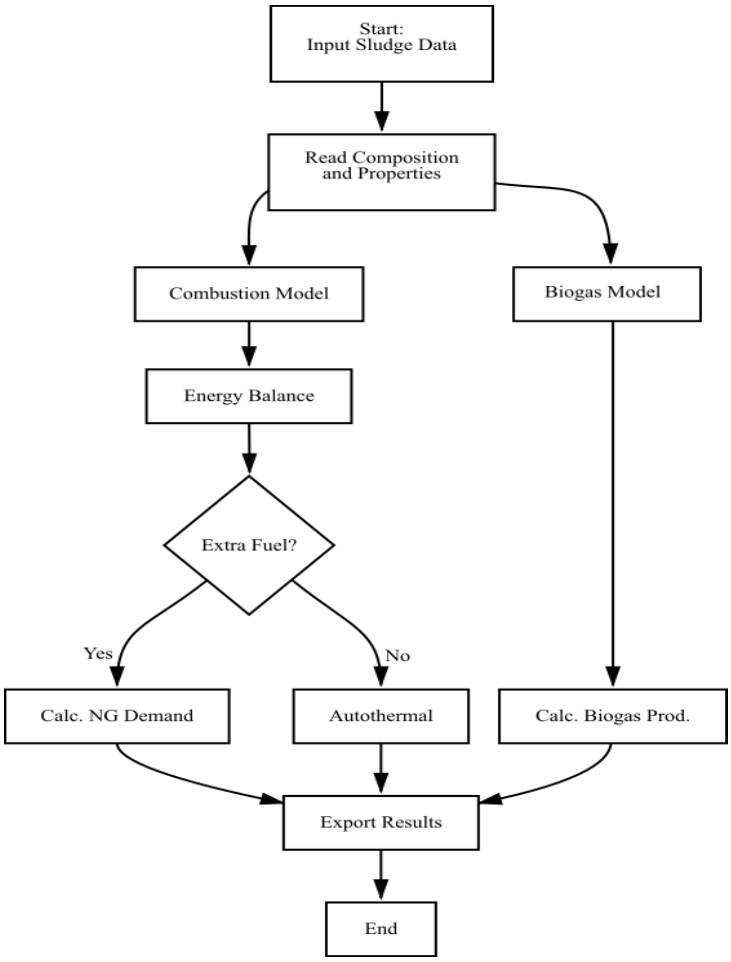

Figure 2. Calculation Algorithm

2.3. Validation of Models

The developed model was validated through both experimental and theoretical studies. The combustion product compositions obtained from the model were compared with those presented in the reference study (Paraschiv et al. [34]) for a solid fuel with the same elemental composition and assuming that combustion occurs with dry air. Overall, good agreement between the values is observed; however, discrepancies are noted in the nitrogen content. The difference in nitrogen is attributed to the exclusion of nitrogen from excess air in the Paraschiv model. The nitrogen content in Paraschiv's study was corrected based on the total moles of the combustion gases. Minor differences between the values are primarily due to rounding errors.

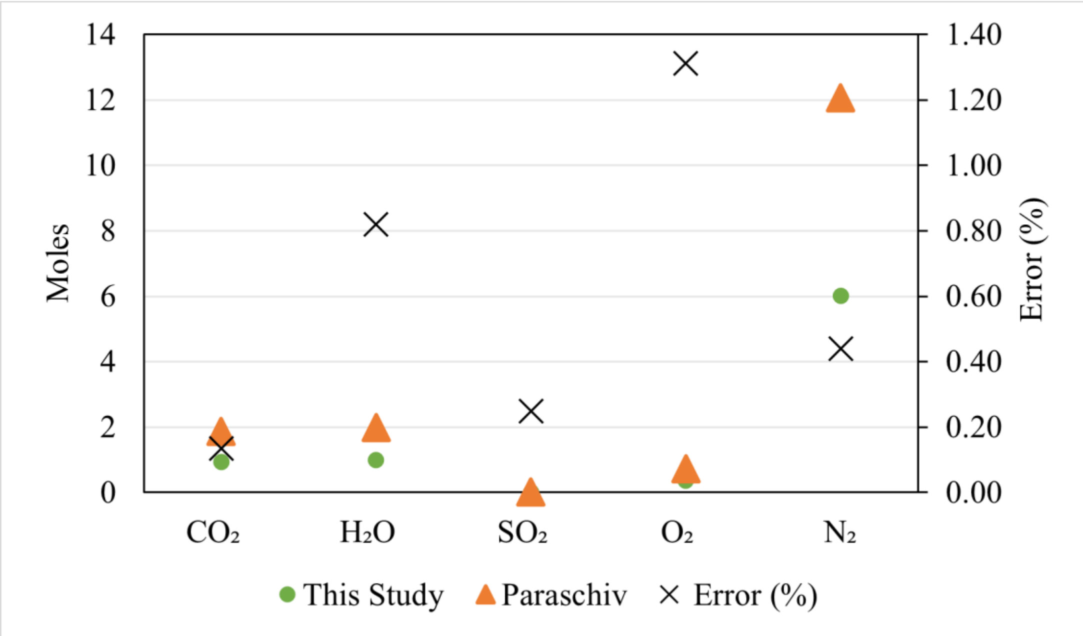

Figure 3. Comparison of Combustion Product Compositions

The natural gas requirement for dewatered sludge combustion was compared with the results reported by Çalbay[35]. The analysis results for all samples are presented in Figure 3. The error margin between the values is approximately ±12%, indicating that the developed model operates consistently and provides reliable predictions. As the lower heating value (LHV) of the sludge increases, the calculated natural gas demand also increases in both models. However, the magnitude of this increase differs between them. In Çalbay's study, the energy required for drying was modeled as the sum of the latent and sensible heat gained by water when heated from the feed temperature (20 °C) to 850 °C, at which point it transitions to the vapor phase. Although this approach is theoretically consistent, in practical applications, the drying process is not limited to the evaporation of free surface moisture. After the surface moisture is fully evaporated, the bound water within the sludge particles must diffuse to the surface and subsequently evaporate for drying to continue, which increases the total energy requirement. In contrast to the Çalbay model, the present study represents the energy required for water evaporation using a fixed specific energy consumption (SEC) value reported in the literature. Various SEC values have been documented for different drying technologies [28,30]. In this study, the energy required to evaporate 1 kg of water was assumed to be 3500 kJ/kg, based on average values reported in the literature.

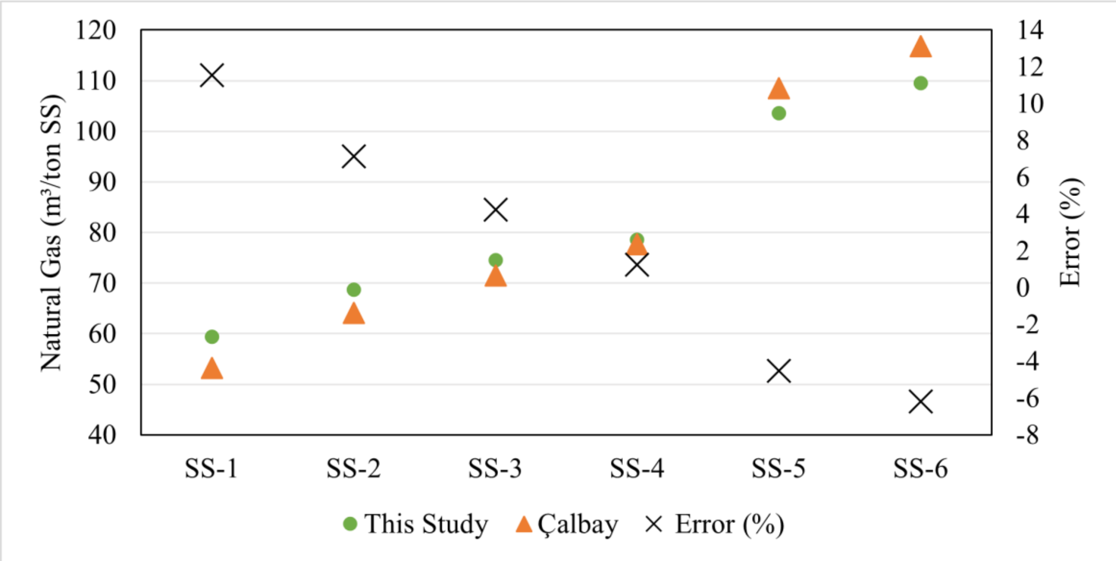

Figure 4. Comparison of Energy Balance for SS Combustion

The biogas potential of sewage sludge has been reported in experimental and theoretical studies to range between 0.3 and 0.6 m³ Biogas/kg VS (volatile solids)[36–38]. Due to the nature of the biochemical processes, the actual biogas production dependens on operating conditions and feedstock characteristics. When the biogas potential is normalized to wet sludge containing 25% TS (total solids) and 80% VS in the solids fraction, the corresponding values decrease to 0.06–0.12 m³ biogas/kg dewatered sludge. The biogas production values calculated by the model, along with literature data, are presented in Figure 5. The comparison indicates that the biogas yield predicted by the model is consistent with reported literature values.

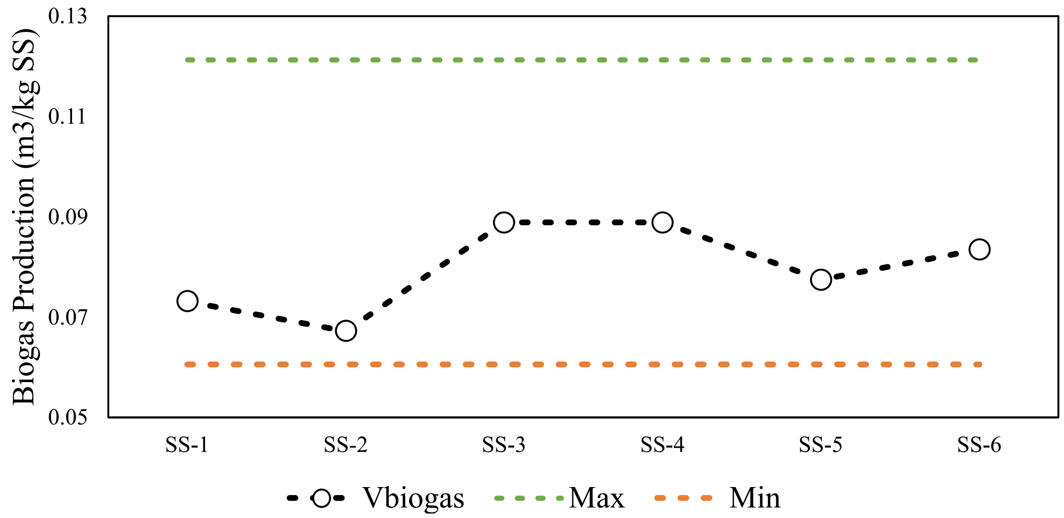

Figure 5. Comparison of Biogas Production from Dewatered SS

2.4. Electricity, Emission and Fuel Cost Calculation

It is assumed that the heat carried by the flue gas at 850°C is recovered using a Waste Heat Recovery Steam Generator (WHRSG) and cooled down to 200°C, producing steam at this temperature. No intermediate heating or regeneration is considered in the Rankine cycle. The WHRSG is assumed to operate with a heat recovery efficiency of 95%, and the Rankine cycle has an assumed efficiency of 26%. The amount of electricity that can be generated in this system is calculated using the Equation 11.

$$E_{\text{combustion}} = Q_{\text{WHRSG}} \times \eta_{\text{WHRSG}} \times \eta_{\text{rankine}} \tag{11}$$

When calculating electricity generation from biogas, the overall efficiency of the engine-generator set is taken into account. In accordance with literature sources, it is assumed to operate at 38% efficiency. The electricity generated from biogas combustion is calculated using the Equation 12.

$$E_{\text{biogas}} = Q_{\text{biogas}} \times \eta_{\text{motor/generator}} \tag{12}$$

The emission factor for electricity generation in Turkey is calculated as 442 kg CO_2/MWh_e[39]. According to the IPCC guidelines, the emission factor for natural gas combustion is determined as 202 kg CO_2/MWh. Since emissions from sludge and biogas combustion are considered biogenic in origin, the emission factor for these processes is calculated as zero. In this context, an emission reduction of 442 kg CO_2/MWh is achieved through electricity generated via sludge incineration and biogas production. However, to establish a complete emission balance, the emissions caused by auxiliary fuel used in the sludge incineration process and the emissions arising during the drying stage (natural gas-fired drying) required for sludge disposal after the biogas process must also be included in the total calculation. For both systems (incineration and biogas), the net emission factors are calculated by dividing the total CO_2 emissions by the electricity generated, as shown in Equation 13.

$$EF = \frac{E_{CO_2}}{E_{electricity}} \quad (13)$$

The economic analysis provides a comprehensive assessment of natural gas costs and the potential revenue from electricity sales. The existing incentive mechanism for biomass power plants guarantees electricity purchase at a fixed price of 133 USD/MWh in Türkiye. Under current market conditions, however, the electricity price stands at approximately 67.82 USD/MWh. The incentive mechanism is therefore expected to have a significant impact on the profitability of such facilities. Additionally, any supplementary natural gas costs must be taken into account. For both the combustion and biogas scenarios, the annual total costs were calculated in detail based on electricity generation, natural gas consumption, and corresponding incentive and market prices for electricity and natural gas.

3. RESULTS AND DISCUSSION

The following section presents the key findings obtained from the developed computational model. The results include the net electricity generation potential, emission factors, annual total emissions, and economic performance indicators for both the combustion and biogas scenarios. The sewage sludge samples (SS-1 to SS-6) were selected to cover a range of calorific values. SS-1 and SS-2 represent high calorific value samples (LHV > 15,000 kJ/kg), SS-3 and SS-4 represent medium calorific value samples (12,000 kJ/kg < LHV < 15,000 kJ/kg), and SS-5 and SS-6 represent low calorific value samples (LHV < 12,000 kJ/kg). Each figure is discussed in detail to highlight the energetic, environmental and financial aspects of the analysed sludge-to-energy pathways.

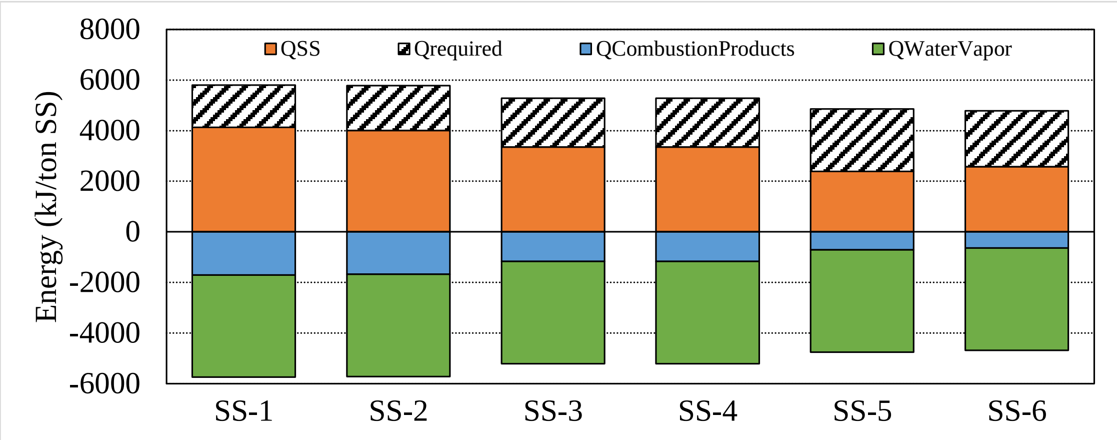

Figure 6. Net Energy Analysis of the Combustion Scenario

Figure 6 presents the energy balance for the incineration of dewatered sewage sludge. The amount of water vaporized is constant for all samples, and consequently, the vaporization energy (Q_{water}) remains approximately 4400 kJ/kg SS. Q_{water} represents the dominant component of the output energy, whereas Qss constitutes the primary contributor to the energy input.

The values of Qss depend on the organic matter content of the sludge, and therefore on its calorific value. The effect of Qss is evident in the figure, as samples SS-1 and SS-2, which exhibit the greatest energy contribution from this parameter, have the highest calorific values among the analyzed samples. Although the contribution of combustion products to the overall energy balance is relatively limited, the variation in their values is noteworthy. This trend can be attributed to the higher organic matter content, which increases the stoichiometric air requirement and consequently results in a larger volume of flue gas generation.

Figure 6 demonstrates that the moisture content of the sludge is a decisive parameter affecting the energy efficiency of the combustion process. High moisture content causes a substantial portion of the chemical energy in the sludge to be consumed for the phase change of water, significantly reducing the net usable thermal energy.

Regarding additional fuel requirements, samples with the lowest calorific values require more than 2200 kJ/kg of supplemental energy. For medium-calorific samples, this requirement is approximately 1900 kJ/kg. In contrast, high-calorific samples demand significantly less supplemental energy, with 1679 kJ/kg for SS-1 and 1777 kJ/kg for SS-2. The difference in supplemental energy between the lowest-calorific sample and the lowest high-calorific sample (SS-1) corresponds to a reduction of at least 23.8%.

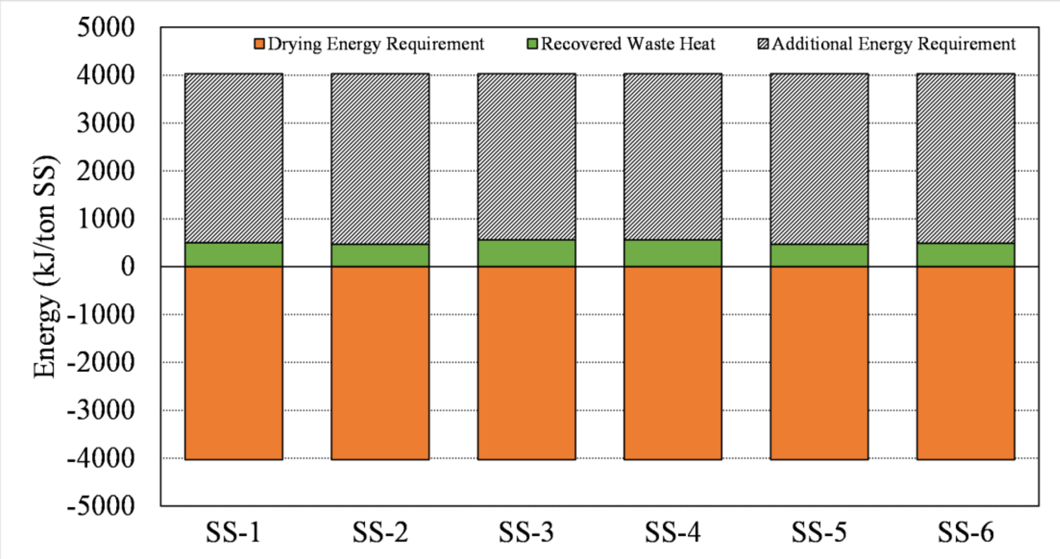

Figure 7. Net Energy Analysis of the Biogas Scenario

The energy balance under the biogas scenario is presented in Figure 7. In the figure, the drying energy demand corresponds to the energy required to dry sludge from 25% TS (total solids) to 85% TS using a constant specific energy consumption (SEC). Consequently, the drying energy requirement has been calculated as approximately 4000 kJ for all samples.

The amount of waste heat recovered from biogas combustion varies (approximately 470–500 kJ) among the scenarios. Overall, the waste heat recovered from the biogas cogeneration unit constitutes approximately 12−15% of the total drying energy requirement.

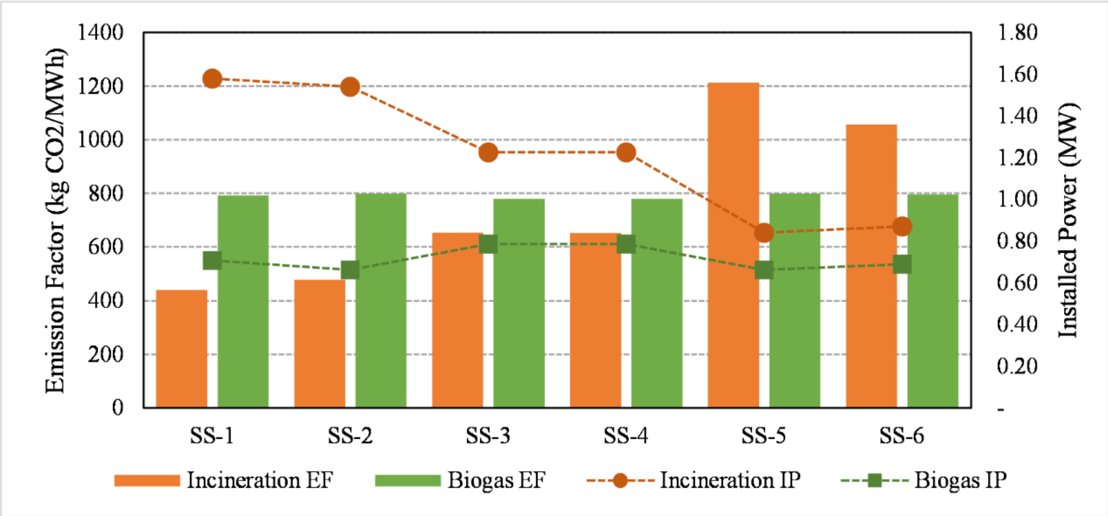

Figure 8. Installed Capacity and Emission Factors from Incineration and Biogas

Figure 8 compares the emission factor (EF) and installed capacity (IP) for six different scenarios in terms of the incineration and biogas production systems. The biogas emission factors remain nearly constant (780-800 kg CO_2/MWh) across all scenarios, exhibiting minimal variation. In contrast, the combustion emission factors show significant variation among the scenarios representing a change from approximately 430-1200 kg CO_2/MWh. For scenarios SS-1 through SS-4, EF is lower than the biogas scenario. Crucially, among all samples and scenarios investigated, only SS-1 yields an emission factor (EF) of 439.88 kg CO2/MWh, which is lower than the emission factor of the Türkiye electricity generation grid (442 kg CO2/MWh).

Regarding the installed capacity, the combustion systems exhibit a general decreasing trend. Specifically, a 46.8% reduction is observed from SS-1 (1.58 MW) to SS-5 (0.84 MW). The installed capacity of the biogas systems displays a stable profile ranging between 0.66 and 0.79 MW.

A significant finding is that, in contrast to the combustion scenario, the biogas based IP is not directly correlated with the calorific value. This outcome is attributed to the influence of the biochemical characteristics of the AD process. Furthermore, that the biogas IP does not reach the level of the combustion process in any scenario suggests the presence of residual organic matter that cannot be utilized within the AD process. Overall, the assessment indicates that biogas systems maintain consistent and low emission performance across all scenarios, whereas combustion systems exhibit substantial scenario-dependent variations. Scenarios SS-5 and SS-6 are notable for their high combustion emission factors, suggesting a disadvantage in terms of carbon footprint.

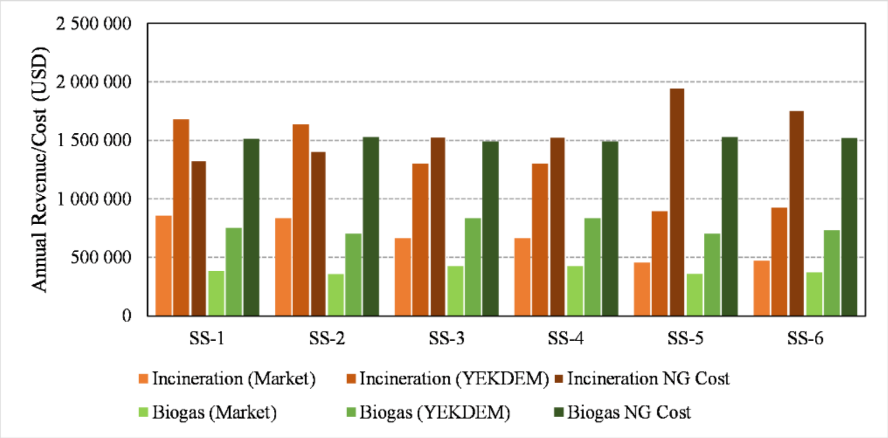

Figure 9. Total Annual Revenue and Natural Gas Cost

Figure 9 illustrates the Annual Revenue/Cost (USD) for both Incineration and Biogas electricity generation systems, highlighting the critical role of the incentivized YEKDEM tariff. As the assumed market price of electricity in Türkiye (USD 67.81/MWh in September 2025) is approximately half the YEKDEM tariff (USD 133/MWh), YEKDEM generates revenues (up to ~$1,638,000) substantially higher than those from market sales (<$850,000).

The cost of natural gas in the combustion scenarios is directly related to the energy requirements, as also illustrated in Figure 6. Consequently, while the initial scenarios (higher calorific value) exhibit low costs, the subsequent scenarios show high costs for low-calorific-value sludges. When natural gas costs and revenues are considered together, none of the samples is profitable at non-incentivized prices. Under incentive pricing, however, profitability is achievable for SS-1 and SS-2.

For the biogas scenario, the natural gas cost required for drying exceeds both incentivized and non-incentivized revenues, indicating that establishing an economically viable facility is not feasible. Overall, the assessment suggests that the YEKDEM incentive significantly improves the economic feasibility of combustion projects. Although biogas sales have a notable effect on revenues, they are insufficient to offset the high natural gas costs. Moreover, assuming electricity production from biogas while neglecting the sludge disposal process could overestimate profitability.

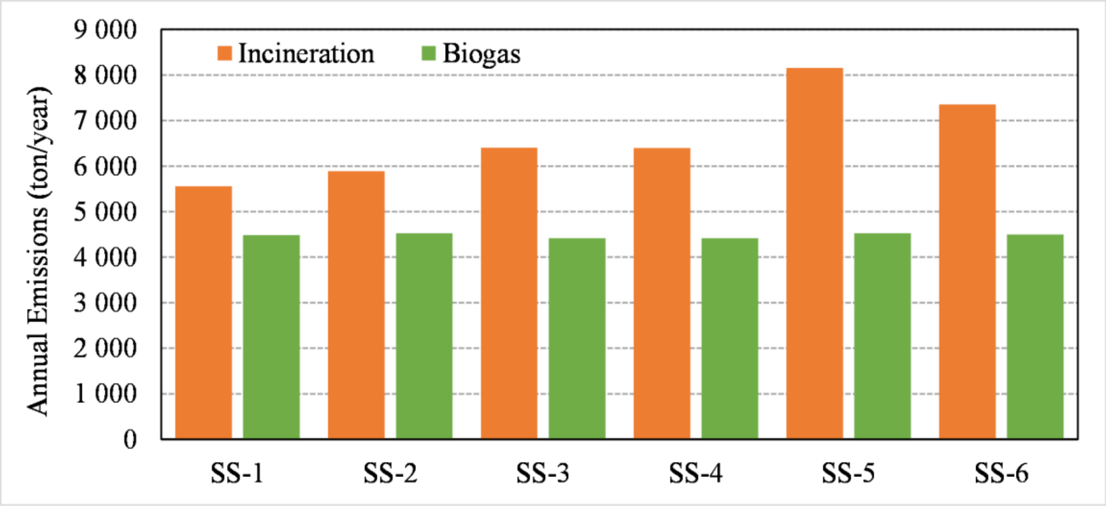

Figure 10. Total Annual Emissions

Figure 10 compares the emissions associated with the final disposal of dewatered sewage sludge, including both incineration and biogas production processes. The most significant finding is that incineration results in substantially higher emissions compared to biogas production. For example, in scenario SS-5, incineration emissions are approximately 8,300 tons/year, whereas biogas emissions are around 4,000 tons/year (between 4,528 and 4,413 tons/year), indicating that incineration emissions are significantly higher.

4. CONCLUSION

This study presents a comprehensive techno-economic and environmental comparison of two sewage sludge-to-energy pathways: direct combustion of dewatered sludge and biogas production through anaerobic digestion. The analysis accounts for the complete sludge management chain, from wastewater treatment plant discharge to final disposal, providing a holistic assessment of energy efficiency, costs, and environmental impacts.

The results demonstrate that the calorific value of sewage sludge is a critical parameter determining the feasibility of combustion-based energy recovery. High-calorific sludges (SS-1 and SS-2, with LHV > 16 MJ/kg) require significantly less supplementary natural gas (1679-1777 kJ/kg) compared to low-calorific samples (>2200 kJ/kg), representing a reduction of at least 23.8%. Only the highest calorific sludge (SS-1) achieved an emission factor (439.88 kg CO_2/MWh) lower than Turkey's electricity grid emission factor (442 kg CO_2/MWh), highlighting the limited environmental benefit of combustion for most sludge qualities.

In terms of installed capacity, combustion systems exhibited higher IP (0.84-1.58 MW) compared to biogas systems (0.66-0.79 MW), with a 46.8% reduction observed from the highest to lowest calorific value samples. However, biogas systems demonstrated more consistent emission performance across all scenarios (780-800 kg CO_2/MWh), contrasting with the substantial variation observed in combustion systems (430-1200 kg CO_2/MWh).

The economic analysis revealed that neither pathway is financially viable without government incentives at current market electricity prices (67.81 USD/MWh). Under the YEKDEM incentive scheme (133 USD/MWh), only high-calorific sludge combustion (SS-1 and SS-2) becomes profitable, generating annual revenues up to approximately 1,638,000 USD. Critically, biogas production was found to be economically unfeasible under both incentivized and non-incentivized conditions, as the natural gas costs required for drying the digestate exceeded all potential revenues.

From an environmental perspective, the total annual emissions analysis showed that incineration consistently produces substantially higher emissions than biogas production. For low-calorific sludge (SS-5), incineration emissions reached approximately 8,300 tons CO_2/year, more than double the biogas scenario emissions (4,000-4,500 tons CO_2/year). This finding underscores the environmental advantage of biogas production, despite its inferior economic performance.
A key contribution of this study is the demonstration that conventional analyses focusing solely on energy generation from biogas, while neglecting the subsequent disposal costs of digested sludge, can lead to significantly overestimated profitability assessments. Similarly, combustion studies that overlook the necessity of supplementary fuel input fail to capture the true economic and environmental costs of the process.

The findings indicate that for sewage sludge management, the optimal pathway depends critically on sludge quality and policy context. High-calorific sludge combustion represents the most economically viable option under current Turkish incentive mechanisms, while biogas production offers superior environmental performance but requires enhanced economic support mechanisms to become financially sustainable. For low-calorific sludges, neither pathway achieves both economic viability and environmental benefits simultaneously, suggesting the need for technological improvements or alternative disposal strategies.

Future research should focus on hybrid approaches that combine anaerobic digestion with advanced thermal treatment of digestate, potentially capturing the environmental benefits of biogas production while addressing the economic challenges of digestate disposal. Additionally, the development of more energy-efficient drying technologies and the optimization of co-digestion strategies with high-energy feedstocks could significantly improve the performance of biogas-based systems.

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DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Süleyman SAPMAZ: Conception and design, data collection, analysis and interpretation of results and manuscript writing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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